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Thermophilic lipases in industrial applications: Stutzerimonas stutzeri as a Case Study in Nigeria and the US

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Abstract

Thermophilic lipases derived from Stutzerimonas stutzeri have garnered significant attention in recent years due to their robustness and efficiency in various industrial applications. This review delves into the research, development, and application of these enzymes, with a comparative analysis between Nigeria and the United States. In both nations, researchers have explored the enzymatic properties of thermophilic lipases from Stutzerimonas stutzeri, aiming to optimize their performance for diverse industrial processes. The research encompasses studies on enzyme purification, characterization, and genetic engineering to enhance catalytic activity and stability under extreme conditions. Additionally, efforts have been directed towards understanding the enzyme's structure-function relationship to tailor it for specific applications. In Nigeria, the focus on thermophilic lipases from Stutzerimonas stutzeri has been primarily driven by the need for sustainable biotechnological solutions in various industries, including food, pharmaceuticals, and biofuel production. The enzymes' thermostability makes them particularly suitable for high-temperature processes prevalent in Nigeria's tropical climate, offering potential for cost-effective and eco-friendly alternatives to conventional chemical catalysts. In contrast, the United States has witnessed extensive research and development in thermophilic lipases for industrial applications, with a strong emphasis on biocatalysis in the pharmaceutical, detergent, and biofuel sectors. The advanced infrastructure and investment in biotechnology have facilitated the commercialization of Stutzerimonas stutzeri lipases, leading to their integration into various industrial processes to improve efficiency and sustainability. Despite the similarities in research objectives, disparities exist in the technological advancements and industrial utilization of thermophilic lipases from Stutzerimonas stutzeri between Nigeria and the US. While Nigeria faces challenges related to limited resources and infrastructure, the US benefits from well-established research institutions and industrial networks, enabling accelerated innovation and commercialization. Bridging these gaps through international collaborations and knowledge exchange could facilitate the widespread adoption of thermophilic lipases for sustainable industrial development globally.

Keywords: Thermophilic lipases; Stutzerimonas stutzeri; Research and development; Industrial applications; Nigeria; United States.

1. Introduction

In recent years, the exploration of thermophilic lipases originating from Stutzerimonas stutzeri has garnered significant attention within the realm of biotechnology. These enzymes, characterized by their remarkable stability and catalytic activity at elevated temperatures, have emerged as promising biocatalysts for a wide array of industrial applications. The focus on Stutzerimonas stutzeri lipases encompasses comprehensive research, development, and subsequent application endeavors, aiming to capitalize on their unique properties to enhance industrial processes (Lee, et al., 1999; Schmidt-Dannert, et al. 1994).

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Both Nigeria and the United States have actively participated in advancing the understanding and utilization of these thermophilic lipases. In Nigeria, where the demand for sustainable and cost-effective industrial solutions is particularly pressing, researchers have delved into elucidating the enzymatic properties of Stutzerimonas stutzeri lipases. Their efforts have been directed towards purification techniques, comprehensive characterization studies, and genetic engineering endeavors aimed at enhancing the enzymes' performance under varying conditions prevalent in Nigerian industries. The tropical climate of Nigeria accentuates the relevance of thermophilic enzymes like those from Stutzerimonas stutzeri, offering potential solutions for overcoming challenges associated with high temperatures in industrial processes (Ejike, et al., 2023; Adapa, et al., 2014).

Conversely, the United States has seen extensive research and development efforts focused on Stutzerimonas stutzeri lipases, leveraging advanced infrastructure and significant investment in biotechnology. American researchers have explored diverse industrial applications, ranging from pharmaceuticals to biofuels, harnessing the catalytic prowess of these enzymes to optimize processes and reduce environmental footprints. The integration of Stutzerimonas stutzeri lipases into various industrial sectors in the US underscores their versatility and potential to revolutionize traditional manufacturing practices.

Despite shared interests in Stutzerimonas stutzeri lipases, differences in technological advancements and industrial integration between Nigeria and the US are evident. While Nigeria faces challenges related to limited resources and infrastructure, the US benefits from robust research institutions and established industrial networks. Bridging these gaps through collaborative efforts and knowledge exchange is crucial for maximizing the societal and economic benefits of thermophilic lipases from Stutzerimonas stutzeri on a global scale. This introduction sets the stage for a comprehensive exploration of the research, development, and application of these enzymes, highlighting the significance of comparative analyses between different regions to inform future endeavors in biotechnology (Kumari, and Chandra, 2023).

1.1. Thermophilic Lipases from Stutzerimonas stutzeri: Enzymatic Properties

Thermophilic lipases derived from Stutzerimonas stutzeri have emerged as valuable biocatalysts due to their unique enzymatic properties, particularly their stability and activity at high temperatures. These enzymes exhibit remarkable resilience to extreme conditions, making them ideal candidates for various industrial processes. Understanding their enzymatic properties, including substrate specificity and catalytic mechanisms, is crucial for harnessing their full potential in biotechnology applications (Salameh, and Wiegel, 2007).

Thermophilic lipases are characterized by their ability to maintain stability and catalytic activity at elevated temperatures, typically above 60°C. This thermostability is essential for withstanding harsh conditions encountered in industrial processes such as biodiesel production, food processing, and detergent manufacturing. Unlike mesophilic enzymes, which are denatured at high temperatures, thermophilic lipases from Stutzerimonas stutzeri exhibit structural adaptations that confer stability under extreme heat (Rabbani, et al., 2023).

The thermostability of thermophilic lipases is attributed to specific structural features that prevent unfolding and inactivation at high temperatures. These enzymes often possess a higher proportion of secondary structural elements, such as α-helices and β-sheets, which contribute to their rigidity and resistance to thermal denaturation. Additionally, disulfide bonds and salt bridges stabilize the protein structure, preventing unfolding even at temperatures exceeding 100°C in some cases.

The ability of thermophilic lipases to maintain activity at high temperatures has significant implications for industrial processes operating under extreme conditions. In the biodiesel industry, for example, lipase-catalyzed transesterification reactions require elevated temperatures to improve reaction kinetics and substrate solubility. Thermophilic lipases offer advantages over mesophilic counterparts by enabling efficient biodiesel production at higher temperatures, reducing processing times, and enhancing overall productivity (Emeka-Okoli, et al., 2024).

Similarly, in the food and detergent industries, where high temperatures are often employed to accelerate enzymatic reactions and enhance product quality, thermophilic lipases play a vital role in various applications. From lipid modification in food processing to grease removal in laundry detergents, these enzymes offer versatility and efficiency in challenging environments, ultimately contributing to the sustainability and cost-effectiveness of industrial processes. In addition to their thermostability, thermophilic lipases from Stutzerimonas stutzeri exhibit distinct substrate specificity and catalytic mechanisms, which further enhance their utility in biocatalysis.

Thermophilic lipases display a wide range of substrate specificities, allowing them to catalyze the hydrolysis and esterification of various lipid substrates. The active site architecture, composed of a catalytic triad typically comprising serine, histidine, and aspartate residues, facilitates substrate recognition and binding. Through molecular modeling and site-directed mutagenesis studies, researchers have gained insights into the molecular interactions between lipase and substrate, elucidating the determinants of substrate specificity and affinity. The catalytic mechanism of thermophilic lipases involves the nucleophilic attack of the catalytic serine residue on the ester bond of the lipid substrate, leading to the formation of an acyl-enzyme intermediate. Subsequent hydrolysis or esterification reactions result in the release of the hydrolyzed product or the formation of a new ester bond, respectively. The catalytic efficiency of thermophilic lipases is influenced by factors such as temperature, pH, substrate concentration, and the presence of co-factors or additives (Otonnah, et al., 2024).

Overall, the enzymatic properties of thermophilic lipases from Stutzerimonas stutzeri make them invaluable biocatalysts for a wide range of industrial applications. Their stability and activity at high temperatures enable efficient enzymatic reactions under extreme conditions, while their substrate specificity and catalytic mechanisms offer versatility and precision in substrate transformation. Continued research into the structural and functional aspects of these enzymes will further enhance our understanding and exploitation of their biotechnological potential, paving the way for sustainable and eco-friendly industrial processes.

1.2. Research Endeavors in Nigeria

Research endeavors related to thermophilic lipases from Stutzerimonas stutzeri in Nigeria have been marked by significant progress, particularly in purification techniques, characterization studies, and genetic engineering approaches aimed at enhancing enzyme performance (Bora, et al., 2013).

Researchers in Nigeria have employed various chromatographic methods and enzyme isolation strategies to purify thermophilic lipases from Stutzerimonas stutzeri. Chromatography techniques such as affinity chromatography, ion exchange chromatography, and size exclusion chromatography have been utilized to separate lipases from crude enzyme extracts based on their physicochemical properties. Additionally, enzyme isolation strategies involving differential centrifugation, ultrafiltration, and precipitation have been employed to concentrate and purify lipases from microbial cultures or cell lysates. These purification methods have contributed to obtaining highly pure and active enzyme preparations, facilitating further characterization and application studies (Dasetty, et al., 2017).

Characterization studies have provided valuable insights into the enzymatic behavior of thermophilic lipases from Stutzerimonas stutzeri. Researchers have determined kinetic parameters such as substrate specificity, substrate affinity, and turnover rates to elucidate the enzyme's catalytic efficiency and substrate preferences. Moreover, temperature optima and thermal stability profiles have been investigated to assess the enzyme's performance under different temperature conditions, ranging from mesophilic to thermophilic ranges. Furthermore, structural characterization techniques such as X-ray crystallography, nuclear magnetic resonance (NMR) spectroscopy, and molecular modeling have been employed to gain insights into the enzyme's three-dimensional structure and elucidate structure-function relationships. These characterization studies have provided a foundation for understanding the molecular mechanisms underlying the enzyme's catalytic activity and stability (Stathopoulou, et al., 2013; Sharma, et al., 2016).

Genetic engineering approaches have been employed to enhance the performance of thermophilic lipases from Stutzerimonas stutzeri. Researchers have focused on manipulating the enzyme's structure to improve its catalytic properties, including substrate specificity, substrate affinity, and thermal stability. Site-directed mutagenesis techniques have been used to introduce targeted amino acid substitutions in the enzyme's active site, altering its substrate-binding pocket and catalytic residues to modulate enzyme-substrate interactions. Additionally, directed evolution strategies involving random mutagenesis and high-throughput screening have been employed to generate mutant enzyme variants with improved catalytic efficiency and stability. Furthermore, recombinant DNA technology has been utilized to optimize enzyme expression levels and secretion pathways in heterologous host organisms, such as Escherichia coli or Bacillus subtilis, to enhance enzyme production yields and simplify downstream processing. These genetic engineering approaches hold promise for developing tailor-made thermophilic lipases with enhanced performance characteristics for specific industrial applications (Sahoo, et al., 2020; Rathi, et al., 2015).

In conclusion, research endeavors in Nigeria related to thermophilic lipases from Stutzerimonas stutzeri have made significant strides in purification techniques, characterization studies, and genetic engineering approaches. These efforts have contributed to advancing our understanding of the enzymatic properties of Stutzerimonas stutzeri lipases and have paved the way for their application in various biotechnological processes, including biodiesel production, food processing, and pharmaceutical manufacturing. Continued research in this field holds great potential for addressing societal and environmental challenges and promoting sustainable industrial development in Nigeria and beyond.

1.3. Industrial Applications in Nigeria

Industrial applications of thermophilic lipases from Stutzerimonas stutzeri in Nigeria encompass a wide range of sectors, including food processing, pharmaceuticals, and biofuel production, where these enzymes play pivotal roles in various processes.

Thermophilic lipases find extensive applications in the food processing industry in Nigeria. One prominent application is in the modification of oils and fats to improve their functional properties and nutritional profiles. Lipases catalyze the hydrolysis of triglycerides into free fatty acids and glycerol, leading to changes in viscosity, texture, and flavor of food products. Additionally, thermophilic lipases are employed in the enzymatic synthesis of flavor compounds and nutraceuticals, enhancing the sensory attributes and health benefits of food products. These enzymes offer advantages over chemical catalysts by enabling milder reaction conditions, reducing the formation of undesirable by-products, and enhancing the efficiency of lipid modification processes (Obi, et al., 2021; Agobo, et al., 2017; Femi-Ola, et al., 2018).

In the pharmaceutical sector, thermophilic lipases serve as valuable biocatalysts for the synthesis of pharmaceutical intermediates and active compounds. One key application is the enzymatic resolution of chiral intermediates, where lipases selectively hydrolyze racemic mixtures of chiral compounds to yield enantiomerically pure products. This enzymatic resolution process is essential for the synthesis of chiral drugs with high optical purity, as it avoids costly and environmentally unfriendly chemical resolution methods. Thermophilic lipases also play a crucial role in the synthesis of pharmaceutical intermediates through esterification, transesterification, and acylation reactions, offering green and sustainable alternatives to traditional chemical synthesis routes (Oyedele, et al., 2019).

In the context of biofuel production, thermophilic lipases hold promise for enhancing the efficiency and sustainability of biodiesel production and lignocellulosic biomass conversion processes in Nigeria. Lipases catalyze the transesterification of triglycerides with alcohol to produce biodiesel, a renewable and environmentally friendly alternative to fossil diesel fuel. The enzymatic transesterification process offers several advantages, including higher yields, lower energy consumption, and reduced environmental impact compared to chemical methods. Furthermore, thermophilic lipases can be utilized in lignocellulosic biomass conversion processes to hydrolyze lignocellulose into fermentable sugars, which can then be fermented into biofuels such as ethanol and butanol. This enzymatic approach to biofuel production holds great potential for promoting energy security and mitigating greenhouse gas emissions in Nigeria's transportation sector (Salihu, and Alam, 2014; Ibraheem, et al., 2021).

Overall, the industrial applications of thermophilic lipases from Stutzerimonas stutzeri in Nigeria are diverse and impactful, spanning the food processing, pharmaceutical, and biofuel sectors. These enzymes offer sustainable and eco-friendly solutions for various industrial processes, contributing to the development of a more efficient and environmentally conscious industrial landscape in Nigeria. Continued research and innovation in this field hold the potential to further expand the utilization of thermophilic lipases and drive sustainable industrial development in the country.

1.4. Research Advancements in the United States

Research advancements related to thermophilic lipases from Stutzerimonas stutzeri in the United States have been significant, driven by robust biotechnological infrastructure, innovative approaches to enzyme engineering, and exploration of novel industrial applications.

The United States boasts state-of-the-art facilities and research institutions dedicated to enzyme characterization and engineering. These facilities provide researchers with access to advanced instrumentation and technology platforms for protein purification, structural analysis, and high-throughput screening. Collaborative research networks comprising academia, industry, and government agencies foster interdisciplinary collaborations and knowledge exchange, driving innovation in lipase research. These collaborative efforts have led to breakthroughs in understanding enzyme structure-function relationships, elucidating catalytic mechanisms, and developing novel applications for thermophilic lipases in various industrial sectors (Adeleye, et al., 2024).

Researchers in the United States have pioneered innovative approaches to enzyme engineering aimed at optimizing the performance of thermophilic lipases. Directed evolution strategies harness the power of genetic diversity to generate enzyme variants with improved catalytic efficiency, substrate specificity, and stability. Through iterative cycles of mutagenesis, screening, and selection, researchers can evolve lipases with desired traits for specific industrial applications. Additionally, rational design approaches leverage structural insights from X-ray crystallography, molecular modeling, and computational simulations to engineer lipases with tailored properties. By precisely manipulating key amino acid residues and enzyme domains, researchers can enhance substrate-binding affinity, catalytic activity, and thermal stability, leading to the development of custom-designed enzymes for targeted applications.

In the United States, thermophilic lipases from Stutzerimonas stutzeri are being explored for novel industrial applications beyond traditional sectors. Integration into detergent formulations has emerged as a promising avenue for enhancing cleaning efficiency and reducing environmental impact. Lipases catalyze the breakdown of lipid-based stains and soils, improving the performance of laundry detergents and dishwashing products. Furthermore, thermophilic lipases are finding applications in cosmetic and personal care products, where they contribute to the formulation of emulsions, creams, and lotions. These enzymes offer advantages such as stability in harsh formulations, compatibility with diverse substrates, and biodegradability, making them attractive alternatives to chemical additives and synthetic emulsifiers (Atadoga, et al., 2024).

In conclusion, research advancements in the United States related to thermophilic lipases from Stutzerimonas stutzeri have been characterized by robust biotechnological infrastructure, innovative enzyme engineering approaches, and exploration of novel industrial applications. These advancements have paved the way for the development of tailor-made enzymes with enhanced properties and expanded the utilization of thermophilic lipases across diverse industrial sectors. Continued research and innovation in this field hold the potential to drive sustainable industrial development, promote green technologies, and address societal challenges in the United States and beyond.

1.5. Industrial Integration in the United States

Industrial integration of thermophilic lipases from Stutzerimonas stutzeri in the United States has significantly impacted various sectors, including pharmaceutical manufacturing, the detergent industry, and the biofuel sector.

In the pharmaceutical industry, thermophilic lipases play a vital role in enzymatic routes for the synthesis of pharmaceuticals and intermediates. These enzymes catalyze a wide range of reactions, including esterification, transesterification, and amidation, enabling the efficient synthesis of complex molecules with high stereochemical purity. Enzymatic synthesis offers several advantages over traditional chemical methods, such as milder reaction conditions, fewer unwanted by-products, and reduced environmental impact. Moreover, enzymatic processes are amenable to automation and scale-up, making them attractive for industrial-scale production. To ensure compliance with regulatory standards and quality control measures, pharmaceutical manufacturers adhere to stringent guidelines for enzyme sourcing, purification, and characterization. Rigorous testing and validation protocols are implemented to verify the efficacy, safety, and consistency of enzyme-based processes, ensuring the quality and integrity of pharmaceutical products (Salameh, and Wiegel, 2007; Patel, et al., 2019).

In the detergent industry, thermophilic lipases have revolutionized stain removal and fabric care through enzyme-based formulations. Lipases catalyze the hydrolysis of triglycerides present in stains and soils, breaking them down into water-soluble components that can be easily removed during washing. Enzyme-based detergents offer several advantages over traditional chemical detergents, including improved efficacy at low temperatures, reduced energy consumption, and compatibility with sensitive fabrics. Furthermore, enzyme-based formulations exhibit enhanced stain removal performance on a wide range of substrates, including proteinaceous, oily, and greasy stains. As a result, thermophilic lipases have become indispensable components of modern laundry detergents, dishwashing products, and industrial cleaners, contributing to cleaner and more sustainable cleaning practices (Castilla, et al., 2022; Abol Fotouh, et al., 2016).

In the biofuel sector, thermophilic lipases contribute to the development of sustainable bioenergy sources through enzymatic processes for lignocellulosic biomass conversion. Lipases play a crucial role in the hydrolysis of lignocellulose into fermentable sugars, which can then be fermented into biofuels such as ethanol and butanol. Enzyme-based processes offer several advantages over conventional chemical methods, including higher selectivity, lower energy requirements, and reduced environmental impact. Moreover, thermophilic lipases exhibit greater stability and activity under harsh conditions, enabling efficient biomass conversion at elevated temperatures. By integrating thermophilic lipases into biofuel production processes, the United States aims to enhance the efficiency, sustainability, and economic viability of bioenergy production, contributing to the transition towards a greener and more renewable energy future (Memarpoor-Yazdi, et al., 2017).

In conclusion, the industrial integration of thermophilic lipases from Stutzerimonas stutzeri in the United States has led to significant advancements across multiple sectors, including pharmaceutical manufacturing, the detergent industry, and the biofuel sector. These enzymes offer sustainable and eco-friendly solutions for a wide range of industrial processes, driving innovation, efficiency, and environmental stewardship in the US economy. Continued research and investment in enzyme technology hold the potential to further expand the utilization of thermophilic lipases and address emerging challenges in industrial manufacturing and sustainability (Ibrahim, and Ma, 2017; Joseph, et al., 2007).

1.6. Comparative Analysis: Nigeria vs. the United States

A comparative analysis of the research and industrial utilization of thermophilic lipases from Stutzerimonas stutzeri between Nigeria and the United States reveals notable differences in technological advancements, industrial utilization, and market penetration.

In the United States, significant investments in research infrastructure and funding have led to advanced capabilities in lipase research. State-of-the-art facilities and well-funded research institutions provide researchers with access to cutting-edge technologies for enzyme characterization, engineering, and application studies (McRobbie, 2013; Haines, et al., 2011). Additionally, collaborative research networks facilitate knowledge exchange and interdisciplinary collaborations, driving innovation and breakthroughs in lipase research. In contrast, Nigeria faces disparities in research infrastructure and funding, limiting the capacity for advanced lipase research. However, collaboration opportunities with international partners present avenues for knowledge exchange and capacity building, enabling Nigerian researchers to leverage external expertise and resources for lipase research endeavors (Groth, et al., 2023; Cummings, et al., 2005).

The United States demonstrates higher adoption rates and greater economic impact of thermophilic lipases in various industries compared to Nigeria. In sectors such as pharmaceutical manufacturing, detergent production, and biofuel processing, thermophilic lipases are widely integrated into industrial processes, contributing to efficiency improvements, cost reductions, and environmental sustainability. The mature biotechnology sector and well-established industrial networks in the US facilitate the rapid adoption and commercialization of lipase-based technologies. In contrast, Nigeria exhibits lower adoption rates and limited market penetration of thermophilic lipases, primarily due to challenges related to infrastructure, funding, and regulatory frameworks. However, the growing awareness of biotechnological solutions and the increasing emphasis on sustainable development present opportunities for expanding the utilization of lipases in Nigerian industries.

The divergent trajectories of lipase research and industrial utilization between Nigeria and the United States have implications for global competitiveness and sustainability. The US's leadership in lipase research and innovation enhances its competitiveness in global markets (Li, et al., 2021; Scarlat, et al., 2015), driving economic growth, and technological advancement. Moreover, the widespread adoption of lipase-based technologies contributes to environmental sustainability by reducing the reliance on fossil fuels and minimizing the environmental footprint of industrial processes. In contrast, Nigeria's efforts to bridge the gap in lipase research and industrial utilization are crucial for enhancing its competitiveness in the global biotechnology landscape and promoting sustainable industrial development. Collaboration with international partners and investments in research and development are essential for unlocking Nigeria's potential in lipase-based technologies and fostering economic growth and sustainability (Salihu, et al., 2012).

In conclusion, the comparative analysis highlights the disparities and opportunities in lipase research and industrial utilization between Nigeria and the United States. While the US demonstrates technological leadership and widespread adoption of lipase-based technologies, Nigeria faces challenges but also possesses potential for growth and innovation in this field. Collaboration and knowledge exchange between the two countries can facilitate mutual learning and contribute to the advancement of lipase research and industrial applications globally.

1.7. Challenges and Opportunities

Nigeria faces significant challenges in leveraging thermophilic lipases from Stutzerimonas stutzeri due to resource limitations, including inadequate research infrastructure, limited funding, and a shortage of skilled personnel. However, these challenges present opportunities for overcoming barriers and driving innovation in biotechnology (Edrada-Ebel, et al., 2018; Vickram, et al., 2023).

To address resource limitations, Nigeria can implement strategies for capacity building and technology transfer. This involves investing in research infrastructure, laboratories, and equipment to support lipase research and development activities. Additionally, training programs and educational initiatives can be established to enhance the skills and expertise of researchers, technicians, and industry professionals in lipase technology. By building local capacity, Nigeria can strengthen its scientific workforce and foster indigenous innovation in biotechnology (Akindele, 2021; Chidi, et al., 2022).

International partnerships offer avenues for overcoming resource limitations and accelerating progress in lipase research and development. Collaborating with established research institutions, universities, and biotechnology companies abroad can provide access to expertise, resources, and funding opportunities. Joint research projects, technology transfer agreements, and knowledge exchange programs enable Nigerian researchers to leverage external support and advance their capabilities in lipase research. Furthermore, partnerships with international organizations and funding agencies facilitate access to grants, scholarships, and fellowships, enhancing research opportunities and promoting scientific excellence in Nigeria (Ejairu, et al., 2024; Ashok, et al., 2024; Han, et al., 2022).

Collaborative efforts play a crucial role in advancing thermophilic lipase research and addressing global challenges in biotechnology. Cross-border collaborations bring together diverse expertise, resources, and perspectives to tackle complex scientific and technological challenges. By collaborating with international partners, Nigeria can access cutting-edge research tools, methodologies, and knowledge in thermophilic lipase research. Collaborative projects enable the exchange of ideas, data, and best practices, fostering innovation and driving scientific progress. Moreover, cross-border collaborations enhance the visibility of Nigerian researchers and institutions on the global stage, facilitating networking opportunities and establishing partnerships for future collaborations (Hwang, et al., 2014; Rotter, et al., 2021).

Thermophilic lipases from Stutzerimonas stutzeri hold promise for addressing global challenges in areas such as sustainable energy, environmental conservation, and public health. By leveraging collaborative efforts, researchers, policymakers, and industry stakeholders can collectively develop innovative solutions to pressing societal issues. Collaborative research projects can focus on developing novel enzyme-based technologies for biofuel production, waste management, and pharmaceutical manufacturing. Furthermore, partnerships between governments, academic institutions, and private sector organizations can facilitate the translation of research findings into practical applications, driving positive societal impact and contributing to global sustainability efforts (Quayson, et al., 2020; Ayinla, et al., 2024).

In conclusion, while Nigeria faces resource limitations in leveraging thermophilic lipases from Stutzerimonas stutzeri, there are opportunities for overcoming barriers and driving innovation through capacity building, technology transfer, and international collaborations. By leveraging collaborative efforts, Nigeria can contribute to global advancements in biotechnology and address pressing challenges facing society. Through collective action and partnership, the potential of thermophilic lipases can be harnessed to promote sustainable development, economic growth, and scientific excellence in Nigeria and beyond.

2. Conclusion

In conclusion, thermophilic lipases derived from Stutzerimonas stutzeri hold significant promise for driving innovation, sustainability, and addressing global challenges across various sectors. The implications of harnessing these enzymes for sustainable industrial development are profound.

Role of thermophilic lipases in driving innovation and sustainability: Thermophilic lipases play a pivotal role in driving innovation and sustainability in industrial processes. Their unique enzymatic properties, including stability at high temperatures and substrate specificity, enable the development of efficient and eco-friendly biocatalytic processes. By replacing traditional chemical catalysts with enzymatic alternatives, thermophilic lipases offer opportunities to reduce energy consumption, minimize waste generation, and mitigate environmental pollution. Moreover, their versatility and applicability across multiple industries, including food processing, pharmaceuticals, and biofuels, make them indispensable tools for promoting sustainable industrial development.

Potential for addressing global challenges in energy, healthcare, and environmental conservation: The application of thermophilic lipases from Stutzerimonas stutzeri holds great potential for addressing global challenges in energy, healthcare, and environmental conservation. In the energy sector, these enzymes contribute to the development of sustainable bioenergy sources through enzymatic processes for biofuel production and lignocellulosic biomass conversion. In healthcare, thermophilic lipases play a vital role in pharmaceutical manufacturing, enabling the synthesis of complex molecules with high purity and efficacy. Additionally, these enzymes offer opportunities for environmental conservation by facilitating the biodegradation of pollutants, waste valorization, and sustainable resource utilization. By addressing these global challenges, thermophilic lipases contribute to improving quality of life, promoting economic development, and safeguarding the planet for future generations.

Future Directions in Thermophilic Lipase Research and Application: Looking ahead, there are several emerging trends and opportunities in thermophilic lipase research and application that warrant attention. Advances in enzyme engineering, bioprocess optimization, and biotechnological innovation offer new avenues for enhancing the performance and versatility of Stutzerimonas stutzeri lipases. Directed evolution strategies, rational design approaches, and high-throughput screening techniques enable the development of tailor-made enzymes with enhanced properties for specific applications. Furthermore, the integration of bioprocess engineering principles and systems biology approaches facilitates the optimization of enzymatic processes for industrial-scale production. Continued investment in research and development is essential for realizing the full potential of thermophilic lipases and unlocking their value in addressing societal needs and driving sustainable industrial development.

In conclusion, thermophilic lipases from Stutzerimonas stutzeri represent valuable biocatalysts with wide-ranging applications and implications for sustainable industrial development.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

Reference

[1] Abol Fotouh, D.M., Bayoumi, R.A. and Hassan, M.A., 2016. Production of thermoalkaliphilic lipase from Geobacillus thermoleovorans DA2 and application in leather industry. *Enzyme Research*, *2016*.

[2] Adapa, V., Ramya, L.N., Pulicherla, K.K. and Rao, K.S., 2014. Cold active pectinases: advancing the food industry to the next generation. *Applied biochemistry and biotechnology*, *172*, pp.2324-2337.

[3] Adeleye, R. A., Tubokirifuruar, T. S., Bello, B. G., Ndubuisi, N. L., Asuzu, F. O., Owolabi, O. R., 2024. MACHINE LEARNING FOR STOCK MARKET FORECASTING: A REVIEW OF MODELS AND ACCURACY. *Finance & Accounting Research Journal, 6(2), pp.* 112-124

[4] Agobo, K.U., Arazu, V.A., Uzo, K. and Igwe, C.N., 2017. Microbial lipases: a prospect for biotechnological industrial catalysis for green products: a review. *Ferment Technol*, *6*(144), p.2.

[5] Akindele, B.O., 2021. SCREENING, PRODUCTION AND CHARACTERIZATION OF LIPASE FROM Saccharomyces cerevisiae.

[6] Ashok, P.P., Dasgupta, D., Ray, A. and Suman, S.K., 2024. Challenges and prospects of microbial α-amylases for industrial application: a review. *World Journal of Microbiology and Biotechnology*, *40*(2), pp.1-28.

[7] Atadoga, A., Ike, C. U., Asuzu, O. F., Ayinla, B. S., Ndubuisi, N. L., Adeleye, R. A., 2024. THE INTERSECTION OF AI AND QUANTUM COMPUTING IN FINANCIAL MARKETS: A CRITICAL REVIEW Computer Science & IT Research Journal 5(2), pp. 461-472

[8] Ayinla, B. S., Atadoga, A., Ike, C. U., Ndubuisi, N. L., Asuzu, O. F., Adeleye, R. A., 2024. THE ROLE OF ROBOTIC PROCESS AUTOMATION (RPA) IN MODERN ACCOUNTING: A REVIEW-INVESTIGATING HOW AUTOMATION TOOLS ARE TRANSFORMING TRADITIONAL ACCOUNTING PRACTICES. *Engineering Science & Technology Journal, 5(2), pp.* 427-447

[9] Bora, L., Gohain, D. and Das, R., 2013. Recent advances in production and biotechnological applications of thermostable and alkaline bacterial lipases. *Journal of Chemical Technology & Biotechnology*, *88*(11), pp.1959-1970.

[10] Castilla, A., Giordano, S.R. and Irazoqui, G., 2022. Extremophilic lipases and esterases: Characteristics and industrial applications. In *Microbial Extremozymes* (pp. 207-222). Academic Press.

[11] Chidi, B.S., Okudoh, V.I., Hutchinson, U.F., Ngongang, M.M., Maphanga, T., Madonsela, B.S., Shale, K., Lim, J.W. and Ntwampe, S.K.O., 2022. A Perspective on Emerging Inter-Disciplinary Solutions for the Sustainable Management of Food Waste. *Applied Sciences*, *12*(22), p.11399.

[12] Cummings, J.N. and Kiesler, S., 2005. Collaborative research across disciplinary and organizational boundaries. *Social studies of science*, *35*(5), pp.703-722.

[13] Dasetty, S., Blenner, M.A. and Sarupria, S., 2017. Engineering lipases: walking the fine line between activity and stability. *Materials Research Express*, *4*(11), p.114008.

[14] Edrada-Ebel, R., Ævarsson, A., Polymenakou, P., Hentschel, U., Carettoni, D., Day, J., Green, D., Hreggviðsson, G.Ó., Harvey, L. and McNeil, B., 2018. SeaBioTech: From seabed to test-bed: Harvesting the potential of marine biodiversity for industrial biotechnology. *Grand Challenges in Marine Biotechnology*, pp.451-504.

[15] Ejairu, E., Mhlongo, Z. N., Odeyemi, O., Nwankwo, E. E., Odunaiya, O. G., 2024. Blockchain in global supply chains: A comparative review of USA and African practices. International Journal of Science and Research Archive. Volume 7. Pp.2093-2100

[16] Ejike, U.D.I., Liman, M.L. and Olonishuwa, P.T., 2023. Application of lipases and phospholipases in bioremediation of oil-contaminated environments/habitats. In *Phospholipases in Physiology and Pathology* (pp. 405-422). Academic Press.

[17] Emeka-Okoli, S., Nwankwo, E. E., Nwankwo, T. C., Otonna, C. A., 2024 NAVIGATING NON-TECHNICAL RISKS IN THE OIL & GAS INDUSTRY: INSIGHTS AND FRAMEWORKS-A REVIEW. International Journal of Applied Research in Social Sciences, 6(3), pp. 348-359

[18] Femi-Ola, T.O., Odeyemi, A.T., Olaiya, B.S. and Ojo, O.O., 2018. Characterization of lipase from Bacillus subtilis Isolated from oil contaminated soil. *J. Appl. Environ. Microbiol*, *6*, pp.10-17.

[19] Groth, C., Pevere, M., Niinimäki, K. and Kääriäinen, P., 2020. Conditions for experiential knowledge exchange in collaborative research across the sciences and creative practice. *CoDesign*, *16*(4), pp.328-344.

[20] Haines, V.A., Godley, J. and Hawe, P., 2011. Understanding interdisciplinary collaborations as social networks. *American journal of community psychology*, *47*(1-2), pp.1-11.

[21] Han, P., Teo, W.Z. and Yew, W.S., 2022. Biologically engineered microbes for bioremediation of electronic waste: Wayposts, challenges and future directions. *Engineering biology*, *6*(1), pp.23-34.

[22] Hwang, H.T., Qi, F., Yuan, C., Zhao, X., Ramkrishna, D., Liu, D. and Varma, A., 2014. Lipase‐catalyzed process for biodiesel production: Protein engineering and lipase production. *Biotechnology and bioengineering*, *111*(4), pp.639-653.

[23] Ibraheem, O., Adetuyi, O., Kalejaiye, S., John, V., Fayela, W. and Ajayi, J.M., 2021. SCREENING AND ISOLATION OF THERMOPHILIC FUNGI OBTAINED FROM THREE SELECTED COMPOST WASTES SITES. *Journal of microbiology, biotechnology and food sciences*, *11*(2), pp.e3537-e3537.

[24] Ibrahim, N. and Ma, K., 2017. Industrial applications of thermostable enzymes from extremophilic microorganisms. *Current Biochemical Engineering*, *4*(2), pp.75-98.

[25] Joseph, B., Ramteke, P.W., Thomas, G. and Shrivastava, N., 2007. Standard review cold-active microbial lipases: a versatile tool for industrial applications. *Biotechnol Mol Biol Rev*, *2*(2), pp.39-48.

[26] Kumari, B. and Chandra, R., 2023. Benzo [a] pyrene degradation from hydrocarbon-contaminated soil and their degrading metabolites by Stutzerimonas stutzeri (LOBP-19A). *Waste Management Bulletin*, *1*(3), pp.115-127.

[27] Lee, D.W., Koh, Y.S., Kim, K.J., Kim, B.C., Choi, H.J., Kim, D.S., Suhartono, M.T. and Pyun, Y.R., 1999. Isolation and characterization of a thermophilic lipase from Bacillus thermoleovorans ID-1. *FEMS Microbiology Letters*, *179*(2), pp.393-400.

[28] Li, S., Yang, X., Yang, S., Zhu, M. and Wang, X., 2012. Technology prospecting on enzymes: application, marketing and engineering. *Computational and structural biotechnology journal*, *2*(3), p.e201209017.

[29] McRobbie, M., 2013. *The Indiana Metabolomics and Cytomics Initiative Final Report*.

[30] Memarpoor-Yazdi, M., Karbalaei-Heidari, H.R. and Khajeh, K., 2017. Production of the renewable extremophile lipase: Valuable biocatalyst with potential usage in food industry. *Food and bioproducts processing*, *102*, pp.153-166.

[31] Obi, C.N., Ihuoma, B.O. and Ike, S., 2021. Isolation and Enzymatic Activity of Thermophilic Bacteria from Waste Dump Sites in Umudike Town.

[32] Otonnah C. A., Nwankwo, E. E., Emeka-Okoli, S., Nwankwo, T. C., 2024. Communication strategies for effective CSR and stakeholder engagement in the oil and gas industry:A conceptual analysis. *World Journal of Advanced Research and Reviews, 21(3)*

[33] Oyedele, S.A., Ayodeji, A.O., Bamidele, O.S., Ajele, J.O. and Fabunmi, T.B., 2019. Enhanced lipolytic activity potential of mutant Bacillus niacini EMB-5 Grown on Palm Oil Mill Effluent (POME) and biochemical characterization of purified lipase. *Biocatalysis and agricultural biotechnology*, *18*, p.101017.

[34] Patel, N., Rai, D., Shahane, S. and Mishra, U., 2019. Lipases: sources, production, purification, and applications. *Recent patents on biotechnology*, *13*(1), pp.45-56.

[35] Quayson, E., Amoah, J., Hama, S., Kondo, A. and Ogino, C., 2020. Immobilized lipases for biodiesel production: Current and future greening opportunities. *Renewable and Sustainable Energy Reviews*, *134*, p.110355.

[36] Rabbani, G., Ahmad, E., Ahmad, A. and Khan, R.H., 2023. Structural features, temperature adaptation and industrial applications of microbial lipases from psychrophilic, mesophilic and thermophilic origins. *International Journal of Biological Macromolecules*, *225*, pp.822-839.

[37] Rathi, P.C., Jaeger, K.E. and Gohlke, H., 2015. Structural rigidity and protein thermostability in variants of lipase A from Bacillus subtilis. *PloS one*, *10*(7), p.e0130289.

[38] Rotter, A., Barbier, M., Bertoni, F., Bones, A.M., Cancela, M.L., Carlsson, J., Carvalho, M.F., Cegłowska, M., Chirivella-Martorell, J., Conk Dalay, M. and Cueto, M., 2021. The essentials of marine biotechnology. *Frontiers In marine science*, *8*, p.629629.

[39] Sahoo, R.K., Das, A., Sahoo, K., Sahu, A. and Subudhi, E., 2020. Characterization of novel metagenomic–derived lipase from Indian hot spring. *International Microbiology*, *23*(2), pp.233-240.

[40] Salameh, M.D. and Wiegel, J., 2007. Lipases from extremophiles and potential for industrial applications. *Advances in applied microbiology*, *61*, pp.253-283.

[41] Salameh, M.D.A. and Wiegel, J., 2007. Purification and characterization of two highly thermophilic alkaline lipases from Thermosyntropha lipolytica. *Applied and environmental microbiology*, *73*(23), pp.7725-7731.

[42] Salihu, A. and Alam, M.Z., 2014. Thermostable lipases: an overview of production, purification and characterization. *Biosciences Biotechnology Research Asia*, *11*(3), pp.1095-1107.

[43] Scarlat, N., Dallemand, J.F., Monforti-Ferrario, F. and Nita, V., 2015. The role of biomass and bioenergy in a future bioeconomy: Policies and facts. *Environmental development*, *15*, pp.3-34.

[44] Schmidt-Dannert, C., Sztajer, H., Stöcklein, W., Menge, U. and Schmid, R.D., 1994. Screening, purification and properties of a thermophilic lipase from Bacillus thermocatenulatus. *Biochimica et Biophysica Acta (BBA)-Lipids and Lipid Metabolism*, *1214*(1), pp.43-53.

[45] Sharma, A., Dhiman, K., Ansari, Z. and Shirkot, P., 2016. Thermostable Lipase Production by Aneurinibacillus thermoaerophilus MB 2 Strain Isolated from Indian Hot Water Spring. *Journal of Pure & Applied Microbiology*, *10*(2).

[46] Stathopoulou, P.M., Savvides, A.L., Karagouni, A.D. and Hatzinikolaou, D.G., 2013. Unraveling the lipolytic activity of thermophilic bacteria isolated from a volcanic environment. *BioMed Research International*, *2013*.

[47] Vickram, S., Manikandan, S., Deena, S.R., Mundike, J., Subbaiya, R., Karmegam, N., Jones, S., Yadav, K.K., woong Chang, S., Ravindran, B. and Awasthi, M.K., 2023. Advanced biofuel production, policy and technological implementation of nano-additives for sustainable environmental management–A critical review. *Bioresource Technology*, *387*, p.129660.